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Cross-education: effects of age on rapid and maximal voluntary contractile characteristics in males

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Abstract

Purpose The purpose of this study was to determine the effect of age on the cross-education of rapid and maximal contractile properties for the knee extensors.

Methods Young ($n = 10$; age $= 21.1 \pm 1.7$ years) and older ($n = 10$; age $= 65.3 \pm 8.3$ years) males performed unilateral isokinetic resistance training (RT) of the knee extensors for 4 weeks. Maximal voluntary isokinetic ($45°$ s^{-1} and $300°$ s^{-1}) and isometric testing was conducted for the trained and untrained leg before and after RT. Peak torque (PT) and acceleration were obtained from isokinetic testing as well as torque at 30 ms (TQ$_{30}$) and 100 ms (TQ$_{100}$) from the $45°$ s^{-1} contraction. PT and rate of torque development were recorded from the isometric contractions.

Results Independent of age, isometric PT (10.1%; $p = 0.006$) as well as PT and acceleration at $300°$ s^{-1} (6.7%; $p = 0.008$ and 4.0%; $p = 0.016$, respectively) increased in the untrained leg. At $45°$ s^{-1}, acceleration was increased (3.6%; $p = 0.021$), but PT remained unchanged ($p = 0.227$). TQ$_{100}$ increased similarly between groups (4.5%; $p = 0.014$), but TQ$_{30}$ increased only in the older group (9.5%; $p = 0.022$).

Conclusions Cross-education of rapid and maximal contractile parameters can be achieved early during unilateral RT independent of age. These findings indicate the potential for particular unilateral RT protocols to be used for older adults in rehabilitative settings to offset disuse-related reductions in contractile function, which are most dramatic in this population.

Keywords Resistance training · Aging · Rate of torque development · Acceleration · Knee extensors

Abbreviations

ACC$_{45}$	Acceleration at $45°$ s^{-1}
ACC$_{300}$	Acceleration at $300°$ s^{-1}
CV	Coefficient of variation
ICC	Intraclass correlation coefficient
MVIC	Maximal voluntary isometric contraction
OM	Older males
PT$_{45}$	Peak torque at $45°$ s^{-1}
PT$_{300}$	Peak torque at $300°$ s^{-1}
RFD	Rate of force development
RT	Resistance training
RTD	Rate of torque development
SEM	Standard error of the measurement
TQ$_{30}$	Torque at 30 ms
TQ$_{100}$	Torque at 100 ms
YM	Young males

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Introduction

Cross-education, the increase in strength of the contralateral, untrained limb after unilateral training, is a well-established adaptation to resistance training (RT). The phenomenon is mediated by neural adaptations as indicated by consistent reports of no training-induced hypertrophy in the untrained limb (Adamson et al. 2008; Farthing and Chilibeck 2003; Ploutz et al. 1994). Specifically, findings from neurophysiological studies suggest that the adaptation occurs at the

supraspinal level (Fimland et al. 2009; Lee and Carroll 2007; Lee et al. 2009). The implications for cross-education, while not fully realized, exist in rehabilitative settings after orthopedic injuries or in post-stroke patients (Farthing and Zehr 2014). Indeed, an increase in strength of the untrained limb accompanied improved range of motion after a period of immobilization (Magnus et al. 2013) and enhanced gait performance in post-stroke patients with hemiplegia (Kim et al. 2015). Despite the positive implications, unilateral RT programs are relatively unused in rehabilitative settings; thus, greater insight on cross-education may serve to enhance awareness of its value for exercise prescription (Collins et al. 2017).

Considering the potential for cross-education to serve populations at risk of musculoskeletal injury or stroke, it is important to also consider the influence of age on the capacity of cross-education. While cross-education has been reported in older adults (Lemmer et al. 2000; Tracy et al. 1999), only a few studies have directly compared cross-education in young and older adults (Bemben and Murphy 2001; Ehsani et al. 2014; Lemmer et al. 2000). Interestingly, the single study examining contralateral strength adaptations for the lower body after unilateral training in young and older adults reported cross-education in the older group only (Lemmer et al. 2000), while evidence for the upper body indicates that age does not influence the capacity for cross-education (Bemben and Murphy 2001; Ehsani et al. 2014; Hughes et al. 1996). Given the importance of the lower body muscles such as the knee extensors for physical functioning (Bryanton and Bilodeau 2017), it is important to provide clarity regarding the potential effect of age on cross-education. Thus, while the utility of cross-education may be greatest in the older population, the influence of age on cross-education has not been clearly elucidated.

The vast majority of cross-education studies have focused on strength as the functional outcome being cross-transferred to the untrained limb after unilateral training. This is at least partially due to the fact that many cross-education investigations have focused on identifying the mechanisms mediating the training-induced adaptation. Indeed, cross-education of rate of force development (RFD) in older adults was only recently reported for the first time (Tøien et al. 2018), which supported previous findings in young adults (Adamson et al. 2008). In addition, it was recently found that maximal velocity and acceleration increased in the untrained knee extensors similarly in young and older males after short-term unilateral training (Hester et al. 2019). Collectively, these recent findings suggest that age does not attenuate cross-education; however, to the best of our knowledge, no study has compared cross-education of rapid force parameters [i.e., RFD/rate of torque development (RTD), force/torque capacity during early phase of contraction] or high-velocity strength in young and older adults.

Importantly, the age-related reduction in rapid force parameters is more dramatic compared to strength (Klass et al. 2008; Thompson et al. 2013). In addition, rapid force capacity of the knee extensors significantly influences overall mobility (i.e., short physical performance battery) in older adults (Osawa et al. 2018). Recently, rapid force capacity was demonstrated to be a significant contributor, independent of strength, to physical functioning tasks such as walking velocity and chair rise ability (Osawa et al. 2018). Further, Altubasi et al. reported a significant, moderate relationship between knee extension RTD and chair rise ability, whereas neither isokinetic nor isometric strength was correlated with physical functioning tasks in older adults (Altubasi 2015). With regard to immobilization, it appears that particular contractile parameters are preferentially reduced in older adults after short-term disuse. For example, decrements in rapid force properties (Hvid et al. 2010) and high-velocity strength (Deschenes et al. 2008) during short-term disuse are markedly more reduced in older adults compared to their younger counterparts.

It is apparent that the ability to quickly produce force is critical for physical functioning and these parameters are preferentially reduced during disuse in older adults. However, little evidence exists regarding the efficacy of unilateral training to induce these adaptations in the untrained limb, and the influence of age is unclear. It is important to determine if cross-education effectively induces rapid force and high-velocity strength adaptations in the untrained limb, especially in older adults, as these adaptive responses would be complementary to strength increases. A non-existent effect of age would suggest the potential for cross-education to be used in clinical settings to at least maintain optimal neuromuscular functioning. Thus, the purpose of this study was to determine the effect of age on cross-education of rapid and maximal contractile properties for the knee extensors. We hypothesized that age would not influence rapid or maximal contractile adaptations in the untrained knee extensors.

Materials and methods

Subjects

Twenty-eight young (18–25 years; $n = 14$) and older (58–78 years; $n = 14$) males were recruited to participate in a 4-week unilateral RT protocol. All subjects were apparently healthy and reported having no metabolic, cardiovascular, musculoskeletal, or nervous system conditions. In addition, subjects reported having no musculoskeletal limitations of the lower body. Further, all subjects reported having no involvement in recreational sports and no experience with RT within the past 6 months. An informed consent, health

and exercise status questionnaire, and physical activity readiness questionnaire were completed by all subjects prior to beginning the study. This study was approved by the University's Institutional Review Board prior to data collection.

Of the initial 28 subjects, four subjects dropped out of the study due to time constraints and two subjects were excluded because of poor adherence to the training protocol (i.e., missed more than 2 training visits); thus, 22 subjects completed this study. Twelve young (YM) and 10 older (OM) males completed 4 weeks of unilateral RT of the dominant leg. Testing sessions were performed before (PRE) and after week 4 of RT (POST). Each dependent variable was measured in the trained and untrained leg. The leg order for testing was randomized at PRE and remained the same at POST for each subject. Testing sessions at POST were performed at approximately the same time of day (± 2 h) as PRE and at least 48 h after the last training session. Subjects were instructed to refrain from caffeine consumption within 12 h of each testing visit. Furthermore, low-intensity physical activity (e.g., walking) was permitted during the study; however, subjects were instructed to not partake in structured aerobic or anaerobic exercise.

Resistance training (RT) protocol

The two groups performed unilateral isokinetic RT of the dominant leg knee extensors three times per week for 4 weeks on a calibrated Biodex System 4 dynamometer (Biodex Medical Systems, Inc. Shirley, NY, USA). Subjects were seated with hands across the chest, restraining straps over the trunk, pelvis, and thigh and the input axis of the dynamometer aligned with the axis of rotation of the knee. Prior to each training session, subjects performed a warm-up consisting of 10 submaximal knee extensions at $45°$ s^{-1} using ~50% of perceived maximal effort. Training sessions consisted of maximal concentric knee extensions at $45°$ s^{-1} for 4 sets of 10 repetitions with 2–3 s of rest between repetitions and a 2 min rest interval between each set. Upon determination of $90°$ knee flexion via manual goniometry, a $70°$ range of motion consisting of knee extension from $90°$ to $160°$ ($180°$ = full extension) was used for each subject. A target line representing the maximal torque determined during the previous testing visit was provided on a computer monitor during each session. Subjects were instructed to "reach the target line as quickly as possible by kicking out as hard and fast as possible throughout the entire range of motion". An emphasis on ballistic intent during contractions was maintained throughout the study. In addition, subjects were instructed to avoid a preceding countermovement and to passively return the leg to $90°$ knee flexion. Further, subjects were instructed and continually reminded to keep their contralateral leg relaxed during the training sessions.

Consistent verbal encouragement and visual biofeedback were provided during each session.

Maximal isometric and isokinetic testing

Prior to maximal testing on the isokinetic dynamometer, subjects performed five submaximal $45°$ s^{-1} isokinetic contractions at 50% of their perceived maximal effort and two submaximal isometric contractions at 50% and 75% of their perceived maximal effort. Three maximal voluntary isometric contractions (MVICs) of the knee extensors were performed at a joint angle of $120°$ with subjects seated and restrained as described for the training procedures. Subsequently, dynamic contractile performance was examined via three maximal isokinetic contractions for the knee extensors at $45°$ s^{-1} and $300°$ s^{-1} using the same range of motion as the training. The order for isokinetic testing was randomized at PRE and the same order was used at POST. Three trials separated by 2-min rest intervals were performed for both isometric and isokinetic testing. Subjects were instructed to kick out as "hard and fast as possible" and to avoid pretension or a countermovement prior to each trial. Further, during MVIC testing, the baseline torque signal was visually examined after each contraction to ensure adherence to instructions. If pretension or a countermovement was visualized, an additional MVIC was performed. In addition, during subsequent analysis, the slope of torque signal prior (100 ms) to torque onset was determined for each contraction and any MVIC with a slope value that exceeded ± 5 N m s^{-1} was discarded (Gerstner et al. 2017). Two subjects from the YM were excluded due to excessive baseline slope in each MVIC trial. Thus, data for 20 (YM = 10; OM = 10) subjects were used for subsequent analyses.

Signal processing

The dynamometer torque and velocity signals were sampled at 2 kHz using a 16-channel Bagnoli Desktop System (Delsys, Inc., Boston, MA, USA). The scaled, gravity corrected torque signal was digitally filtered with a zero lag, low-pass (50 Hz) Butterworth filter using custom written software (LabVIEW, National Instruments, Austin, TX). In addition, for isokinetic contractions, the scaled velocity signal was digitally filtered with a zero lag, low-pass (10 Hz) Butterworth filter. For MVICs, peak torque (PT_{ISOM}) was considered the highest 500 ms rolling average. Peak RTD was derived from the linear slope of the torque-time curve ($\Delta torque/\Delta time$; RTD_{PK}) and was defined as the highest 20 ms rolling slope value. Early RTD was obtained from contraction onset to 30 ms (RTD_{0-30}), while late RTD was acquired from 100 to 200 ms ($RTD_{100-200}$). Since rapid torque capacity was of primary interest for the current study, similar to Barry et al. (2005), the MVIC trial demonstrating

the highest $RTD_{0–200}$ was used for subsequent analysis. A torque onset of 2.5 N m was used for the MVIC torque signal. For the isokinetic contractions, the highest 5 ms rolling average for the torque signal was considered peak torque for both $45° \text{ s}^{-1}$ (PT_{45}) and $300° \text{ s}^{-1}$ (PT_{300}). Acceleration for each isokinetic velocity was calculated as the linear slope of the velocity–time curve (Δvelocity/Δtime) from velocity onset, defined as $2° \text{ s}^{-1}$ (Thompson et al. 2014), to $45° \text{ s}^{-1}$ (ACC_{45}) and $300° \text{ s}^{-1}$ (ACC_{300}). Finally, for the $45° \text{ s}^{-1}$ contractions, torque at 30 ms (TQ_{30}) (i.e., early torque capacity) and 100 ms (TQ_{100}) (i.e., late torque capacity) after achieving $45° \text{ s}^{-1}$ (i.e., initiation of load range) was acquired. The torque and velocity signals were visualized during post-processing to ensure that PT_{45}, TQ_{30}, TQ_{100}, and PT_{300} occurred during the load range. An example of the torque and velocity signals produced during isokinetic testing at $45° \text{ s}^{-1}$ by an older male is displayed in Fig. 1. The isokinetic contraction producing the highest peak torque for the $45° \text{ s}^{-1}$ and $300° \text{ s}^{-1}$ contractions was used for subsequent analysis. Test–retest reliability for each dependent variable was calculated for a sub-sample of older males and can be seen in Table 1. Intraclass correlation coefficients (ICCs) were calculated using the 3.1 model (Shrout and Fleiss 1979; Weir 2005), while standard error or measurement (SEM) was calculated as the square root of the mean square error term and coefficient of variation (CV) was calculated as SEM relative to the grand mean.

Statistical analyses

Since the primary focus was on the effects of unilateral training on the non-dominant knee extensors, baseline comparisons between groups were made with independent samples t tests using the dependent variables obtained
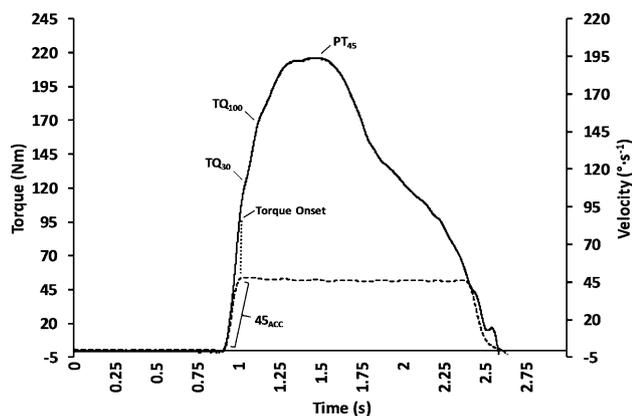
Table 1 Reliability data for each dependent variable

Variable	ICC	SEM	CV (%)
PT_{ISOM}	0.623	22.34	13.20
RTD_{PK}	0.882	154.90	11.87
$RTD_{0–30}$	0.721	137.54	29.62
$RTD_{100–200}$	0.513	124.62	30.17
$RTD_{0–200}$	0.751	116.74	15.53
PT_{45}	0.770	23.34	14.59
TQ_{30}	0.801	13.15	14.19
TQ_{100}	0.848	15.10	12.30
ACC_{45}	0.724	37.46	6.57
PT_{300}	0.947	5.70	7.33
ACC_{300}	0.198	431.31	21.10

from the non-dominant leg. Tukey's HSD post hoc analyses were performed when appropriate. Two-way [group (YM vs. OM) × time (PRE vs. POST)] analyses of variance were used to compare the effects of RT between groups for the trained and untrained leg separately. If an interaction was revealed, dependent samples t tests were performed for each group to assess for changes from PRE to POST. Equality of variances was tested using Levene's Test for Equality of Variances. Statistical analyses were performed using PASW software version 22.0 (SPSS Inc, Chicago, IL, USA) and an alpha level of $p \leq 0.05$ was used to determine statistical significance. In the case of a significant interaction, an alpha level of $p \leq 0.025$ was used to determine statistical significance for the dependent samples t tests. Effect size was reported using partial eta squared (η_p^2) for ANOVA analyses and as Cohen's d for t tests analyses. All data are reported as mean $\pm$ SD, unless noted otherwise.

Results

Baseline comparisons

Subject characteristics for each group are displayed in Table 2. The OM were older ($p < 0.001$; $d = 7.15$) and had a greater body mass ($p = 0.026$; $d = 1.13$) and body mass index ($p = 0.035$; $d = 1.02$). PT_{45} ($p = 0.012$; $d = 1.25$), PT_{300} ($p < 0.001$; $d = 2.41$), TQ_{30} ($p = 0.013$; $d = 1.24$), TQ_{100} ($p = 0.002$; $d = 1.60$), PT_{ISOM} ($p = 0.024$; $d = 1.10$), RTD_{PK} ($p = 0.011$; $d = 1.32$), $RTD_{100–200}$ ($p = 0.024$; $d = 1.39$), $RTD_{0–200}$ ($p = 0.001$; $d = 1.79$) and ACC_{300} ($p = 0.028$; $d = 1.07$) were greater in the YM compared to the OM at baseline. There were no differences between groups for ACC_{45} ($p = 0.688$; $d = 0.18$) or $RTD_{0–30}$ ($p = 0.757$; $d = 0.14$).

Fig. 1 Example of torque (solid) and velocity (dashed) signals during an isokinetic contraction at $45° \text{ s}^{-1}$ for an older male and the corresponding variables including acceleration, torque at 30 ms (TQ_{30}) and 100 ms (TQ_{100}) after onset, and peak torque (PT_{45})

Effects of unilateral training on the untrained leg

There was no interaction ($p = 0.159$; $\eta_p^2 = 0.10$) or main effect for time ($p = 0.227$; $\eta_p^2 = 0.08$) for PT_{45} (Fig. 2a). An interaction was demonstrated for TQ_{30} ($p = 0.031$; $\eta_p^2 = 0.23$), and follow-up analyses revealed that TQ_{30} increased in the OM (9.5%; $p = 0.022$; $d = 0.87$) but remained unchanged in the YM (-0.002%; $p = 0.915$; $d = 0.03$). There was no interaction ($p = 0.128$; $\eta_p^2 = 0.12$) for TQ_{100}; however, a main effect for time ($p = 0.014$; $\eta_p^2 = 0.28$) was demonstrated as TQ_{100}

increased (4.5%) regardless of group (Fig. 3a). There was no interaction ($p = 0.672$; $\eta_p^2 = 0.01$) for ACC_{45}; however, a main effect for time ($p = 0.021$; $\eta_p^2 = 0.26$) was demonstrated as ACC_{45} increased (3.6%) regardless of group (Fig. 4a). No interaction ($p = 0.896$; $\eta_p^2 = 0.00$) was demonstrated for PT_{300}, but a main effect for time ($p = 0.008$; $\eta_p^2 = 0.32$) was revealed as PT_{300} increased (6.7%) regardless of group (Fig. 2a). Similarly, no interaction ($p = 0.134$; $\eta_p^2 = 0.121$) was present for ACC_{300}, but a main effect for time ($p = 0.016$; $\eta_p^2 = 0.28$) was revealed since both groups increased (4.0%)

Table 2 Subject characteristics for the young and old males

Group	n	Age (years)	Body mass (kg)	Height (cm)	BMI (kg m^2)
Young males	10	22.1 ± 1.7	78.6 ± 14.5	176.3 ± 8.1	25.5 ± 6.6
Older males	10	$65.3 \pm 8.3*$	$93.8 \pm 12.1*$	173.6 ± 4.3	$31.1 \pm 3.8*$

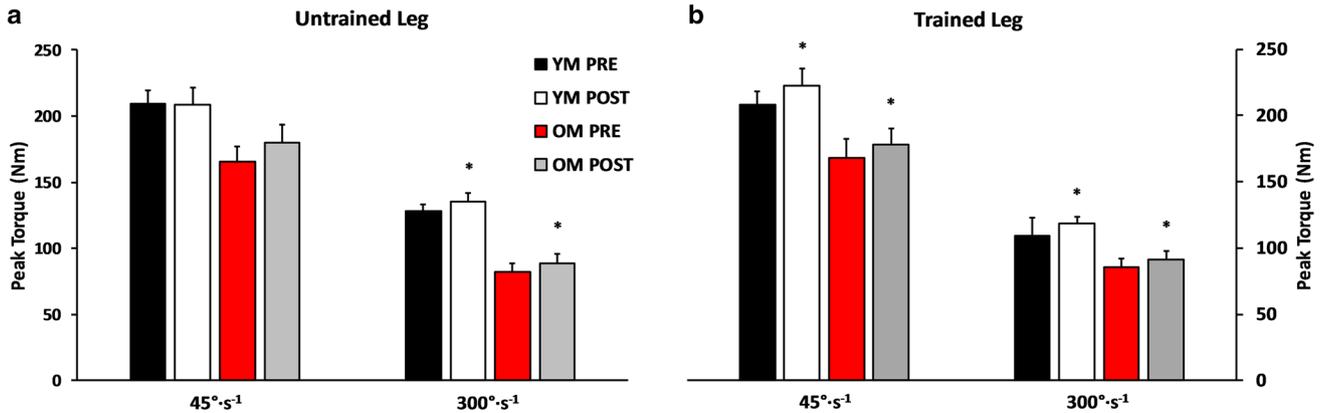*Significantly greater in older males ($p < 0.05$)

Fig. 2 Isokinetic peak torque before (PRE) and after resistance training (POST) for the young (YM) and older males (OM) in the **a** untrained and **b** trained leg. Error bars represent SEM. *Significantly greater at POST when collapsed across both groups
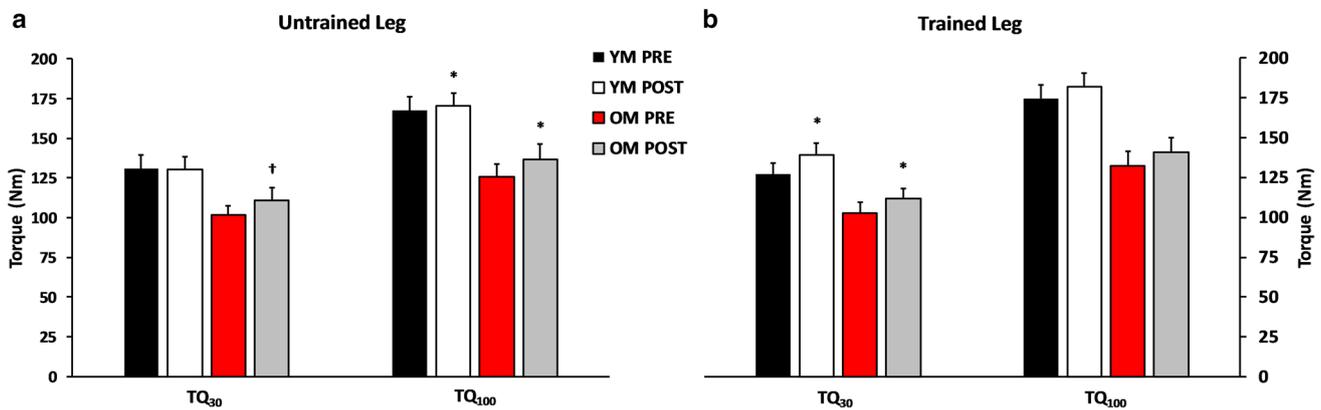
Fig. 3 Torque at 30 ms (TQ_{30}) and 100 ms (TQ_{100}) before (PRE) and after resistance training (POST) for the young (YM) and older males (OM) in the **a** untrained and **b** trained leg. Error bars represent SEM.

†Significantly greater increase at POST compared to YM, *significantly greater at POST when collapsed across both groups
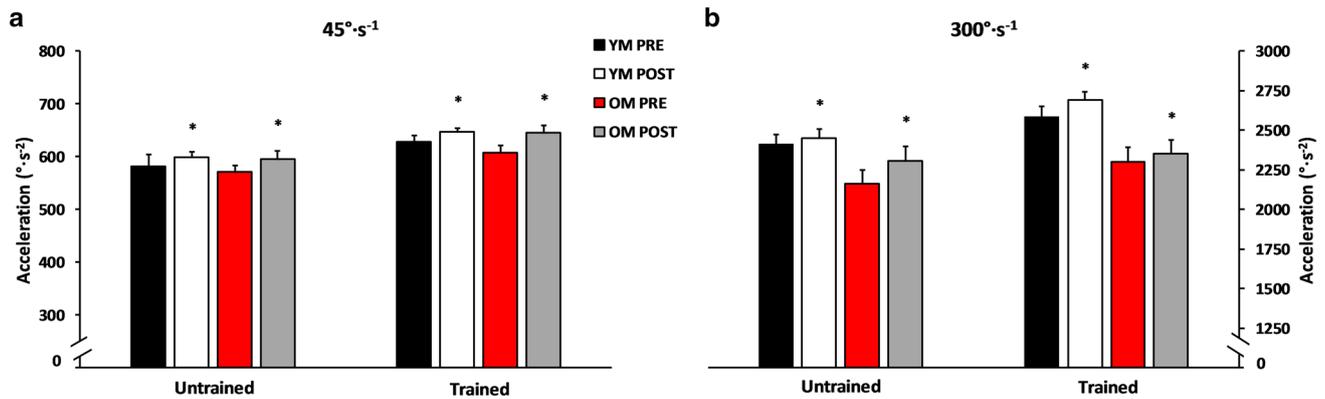
Fig. 4 Acceleration at **a** 45° s^{-1} and **b** 300° s^{-1} before (PRE) and after resistance training (POST) for the young (YM) and older males (OM) in the untrained and trained leg. Error bars represent SEM. *Significantly greater at POST when collapsed across both groups

similarly (Fig. 4a). PT$_{ISOM}$ increased (10.1%) similarly in both groups as indicated by a non-significant interaction ($p = 0.545$; $\eta_p^2 = 0.02$) and significant main effect for time ($p = 0.006$; $\eta_p^2 = 0.35$) (Fig. 5a). No interactions or main effects for time were revealed for RTD$_{PK}$ ($p = 0.052$; $\eta_p^2 = 0.19$ and $p = 0.423$; $\eta_p^2 = 0.03$, respectively), RTD$_{0-30}$ ($p = 0.384$; $\eta_p^2 = 0.04$ and $p = 0.971$; $\eta_p^2 = 0.00$, respectively), RTD$_{100-200}$ ($p = 0.171$; $\eta_p^2 = 0.102$ and $p = 0.29$; $\eta_p^2 = 0.06$, respectively), or RTD$_{0-200}$ ($p = 0.698$; $\eta_p^2 = 0.15$ and $p = 0.400$; $\eta_p^2 = 0.40$, respectively) (Table 3).

Effects of unilateral training on the trained leg

There was no interaction for PT$_{45}$ ($p = 0.710$; $\eta_p^2 = 0.00$), but a main effect for time ($p = 0.050$; $\eta_p^2 = 0.19$) was demonstrated as PT$_{45}$ increased (6.5%) regardless of group (Fig. 2b). There was no interaction for TQ$_{30}$ ($p = 0.676$; $\eta_p^2 = 0.01$), but a main effect for time ($p = 0.010$; $\eta_p^2 = 0.31$) was revealed as TQ$_{30}$ increased (9.2%) regardless of group

(Fig. 3b). No interaction ($p = 0.950$; $\eta_p^2 = 0.00$) or main effect for time ($p = 0.105$; $\eta_p^2 = 0.13$) was demonstrated for TQ$_{100}$ (Fig. 3b). No interaction ($p = 0.322$; $\eta_p^2 = 0.05$) was demonstrated for ACC$_{45}$, but a main effect for time ($p = 0.009$; $\eta_p^2 = 0.32$) was revealed indicating that both groups increased (4.5%) similarly (Fig. 4b). Likewise, there was no interaction for PT$_{300}$ ($p = 0.330$; $\eta_p^2 = 0.05$) (Fig. 2b) or ACC$_{300}$ ($p = 0.280$; $\eta_p^2 = 0.06$) (Fig. 4b), but a main effect for time ($p = 0.001$; $\eta_p^2 = 0.45$) was demonstrated for both PT$_{300}$ (+8.0%) and ACC$_{300}$ (+3.3%), respectively. No interaction ($p = 0.200$; $\eta_p^2 = 0.08$) was demonstrated for PT$_{ISOM}$, but a main effect for time ($p < 0.001$; $\eta_p^2 = 0.72$) indicated that both groups increased (21.5%) similarly (Fig. 5b). Finally, no interactions or main effects for time were revealed for RTD$_{PK}$ ($p = 0.440$; $\eta_p^2 = 0.03$ and $p = 0.175$; $\eta_p^2 = 0.10$, respectively), RTD$_{0-30}$ ($p = 0.578$; $\eta_p^2 = 0.01$ and $p = 0.322$; $\eta_p^2 = 0.05$, respectively), RTD$_{100-200}$ ($p = 0.454$; $\eta_p^2 = 0.03$ and $p = 0.482$; $\eta_p^2 = 0.02$,
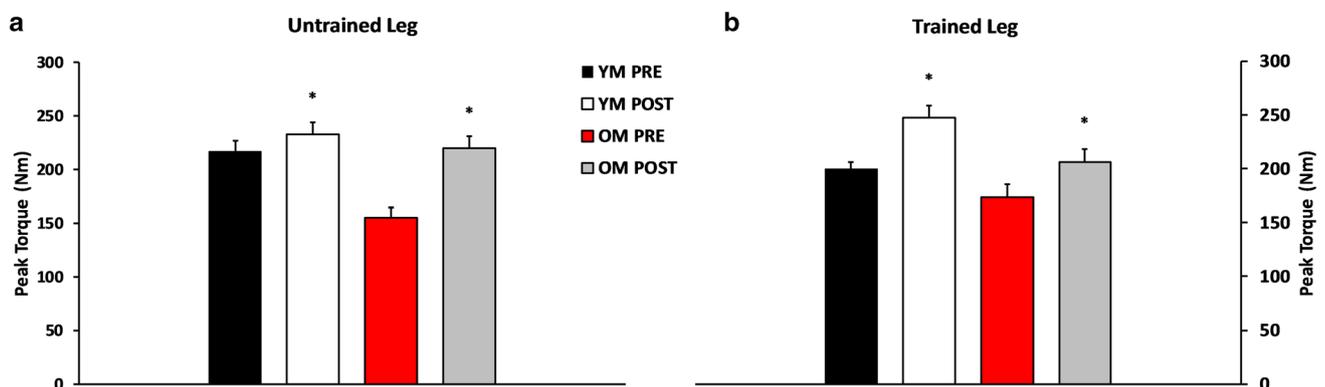

Fig. 5 Isometric peak torque before (PRE) and after resistance training (POST) for the young (YM) and older males (OM) in the **a** untrained and **b** trained leg. Error bars represent SEM. *Significantly greater at POST when collapsed across both groups

Table 3 Rate of torque development variables (mean ± SD) for the untrained and trained leg before (PRE) and after (POST) resistance training

Variable	Untrained leg		Trained leg	
	Pre	Post	Pre	Post
Young males				
RTD_{PK}	1854.54 ± 501.54*	1747.05 ± 415.44	1891.80 ± 389.60	1764.23 ± 247.50
RTD_{0-30}	487.23 ± 264.12	446.53 ± 164.89	496.71 ± 190.20	519.35 ± 159.25
$RTD_{100-200}$	657.99 ± 115.95	727.37 ± 77.72	628.00 ± 164.45	626.43 ± 136.15
RTD_{0-200}	1127.80 ± 194.75*	1146.66 ± 174.77	1109.83 ± 163.61	1106.27 ± 108.56
Older males				
RTD_{PK}	1299.76 ± 319.31	1521.82 ± 415.36	1415.58 ± 382.75	1379.46 ± 387.45
RTD_{0-30}	457.53 ± 137.45	501.68 ± 217.80	469.65 ± 210.73	549.13 ± 303.57
$RTD_{100-200}$	486.25 ± 130.44	476.78 ± 188.35	440.80 ± 140.96	490.15 ± 208.31
RTD_{0-200}	825.01 ± 138.84	875.58 ± 219.15	816.59 ± 146.34	809.60 ± 171.53

*Significantly greater in young males ($p < 0.05$)

respectively), or RTD_{0-200} ($p = 0.636$; $\eta_p^2 = 0.01$ and $p = 0.827$; $\eta_p^2 = 0.003$, respectively) (Table 3).

Discussion

The purpose of this study was to determine the effect of age on cross-education of rapid and maximal contractile properties for the knee extensors. To the best of our knowledge, this is the first study to directly examine the influence of age on cross-education of rapid torque characteristics. The primary finding was that age generally did not alter adaptations in either, the trained or untrained limb, after 4 weeks of unilateral RT. Indeed, OMs increased strength and acceleration similarly compared to YMs, while early isokinetic torque capacity (i.e., TQ_{30}) increased only in the OMs. Secondarily, it was determined that strength and acceleration increased similarly between groups for the trained leg.

While there is an abundance of evidence demonstrating cross-education of strength in young adults, there are surprisingly few reports comparing the effect of age on cross-education. Cross-education of strength was previously found to be similar between young and older adults (Bemben and Murphy 2001; Ehsani et al. 2014); however, whether or not age influences the cross-education of rapid contractile parameters remains unclear. Adamson et al. were among the first to demonstrate the cross-transfer of RFD in young adults (Adamson et al. 2008), while Tøien et al. recently reported similar findings for the plantar flexors, for the first time, in older adults (Tøien et al. 2018). In addition, maximal velocity adaptations in the untrained leg were recently reported to increase similarly in young and older males after short-term unilateral training (Hester et al. 2019). The current findings provide further support for the capacity of cross-education in older adults and extend previous findings to additional rapid contractile characteristics. The training-induced increases in late torque capacity, acceleration, and strength (isometric and $300° s^{-1}$) in the untrained leg were unaffected by age. Interestingly, early torque capacity at $45° s^{-1}$ (i.e., TQ_{30}) only increased in OM, and RTD_{PK} nearly increased more in OM compared to YM ($p = 0.052$; −5.2% vs. 17.1%, respectively), although a small effect was associated with the latter finding. In addition, while not statistically significant, the training-induced relative changes for TQ_{100} (+1.6% vs. +8.3%) and RTD_{0-30} (−8.4% vs. +9.6%) favored the OM as well. However, caution should be used when interpreting our RTD_{0-30} data due to the relatively high degree of error. Recently, Tøien et al. reported slightly higher RT-induced increases in RFD compared to strength for the untrained limb (17% vs. 10%, respectively) in older adults; however, no age-related comparisons were made (Tøien et al. 2018). Speculatively, while the current findings are preliminary, it is possible that older adults demonstrate a greater capacity for cross-education of force production during rapid movements compared to young adults. Nevertheless, it appears that unilateral RT training is highly effective for inducing rapid contractile adaptations in the untrained limb and age does not attenuate these adaptations. Follow-up cross-education studies involving direct age-related comparisons are warranted to elucidate whether or not age influences the cross-transfer of strength or rapid contractile parameters. The lack of a training-induced change for early and late RTD in the current study was likely partially influenced by large measurement variability and lack of testing specificity, although Tillin et al. also reported no changes in rapid isometric force parameters for the untrained leg in young males after 4 weeks of explosive isometric RT (Tillin et al. 2012). Since the magnitude of cross-education is specific to contraction type (Hortobágyi et al. 1997; Seger et al. 1998), future studies examining the influence of age on cross-education should likely utilize isometric or multimodal training and isometric testing to optimally assess rapid force adaptations. Interestingly, cross-education of strength

occurred at non-specific testing velocities (i.e., $0°$ s^{-1} and $300°$ s^{-1}) and not at the training velocity, which contrasts with previous research (Farthing and Chilibeck 2003; Seger et al. 1998) demonstrating velocity specificity. The rationale for this finding is unclear; however, it is possible that the emphasis placed on ballistic contractions during training induced neural adaptations primarily mediating rapid contractile function (Tillin and Folland 2014). In addition, the high degree of effort during the initial aspect of the RT contractions, when an isometric state is more closely being mimicked, may have diminished the stimulus during the later aspect of the contraction when PT would likely occur. This rationale may be indirectly supported by the relatively small effect demonstrated for PT$_{45}$ ($\eta_p^2 = 0.19$) as compared to TQ$_{30}$ ($\eta_p^2 = 0.31$) in the trained leg, which indicates the preferential effect of the RT on early torque capacity as opposed to maximal torque capacity.

Acceleration during slow- and high-velocity knee extensions increased similarly in the YM and OM, although high-velocity acceleration (i.e., ACC$_{300}$) demonstrated 'poor' reliability; thus, caution is warranted for this interpretation. Nevertheless, this finding is relevant because acceleration is substantially reduced in older adults (Petrella et al. 2005; Thompson et al. 2014). This expands upon the findings of Hester et al. who found that RT-induced increases in acceleration during a maximal, unloaded knee extension were similar between young and older males (Hester et al. 2019). In that study, acceleration was assessed throughout a greater range of motion as compared to the current study; therefore, it appears that the ability to increase velocity quickly during early and later phases of muscle contraction can be positively affected in the untrained limb after ballistic unilateral RT. Importantly, optimal velocity (i.e., velocity at which peak power occurs) derived from knee extension (Clémençon et al. 2008) and multi-joint, lower body testing (Kozicka and Kostka 2016) is a significant predictor of physical functioning in older adults. Further, since peak power typically occurs before peak velocity is achieved, the ability to accelerate quickly to optimal velocity is likely more important than peak velocity for power output. Collectively, these findings indicate the potential for adaptations that may provide a complementary effect to an increase in strength during immobilization or in post-stroke patients. In consideration of these recent findings, ballistic-oriented contractions during unilateral RT may be particularly beneficial for inducing several parameters (e.g., early torque capacity, peak velocity, acceleration) associated with improved neuromuscular functioning in the untrained limb, rather than strength alone. For example, strength was reported to be dramatically more reduced at higher velocities compared to slower velocities in post-stroke patients (Lum et al. 2004); thus, the inclusion of ballistic-oriented contractions during unilateral training

may preferentially attenuate the loss of velocity capacity and high velocity strength in the affected limb. However, future cross-education research directly comparing ballistic vs. non-ballistic unilateral training adaptations is warranted for more clarification. Further, studies involving limb immobilization or post-stroke patients are needed to verify the efficacy of this RT methodology for improving function in the affected limb.

With regard to the trained leg, our findings support previous research demonstrating that short-term (≤ 6 weeks) RT-induced strength changes are typically similar between young and older adults (Barry et al. 2005; Bemben and Murphy 2001; Cannon et al. 2007; Christie and Kamen 2010). While there are fewer reports regarding the influence of age on adaptations in rapid contractile parameters, Barry et al. reported similar increases in RFD for young and older adults in the upper body (Barry et al. 2005). In the current study, similar to the untrained leg, RTD was unaffected by RT in the YM and OM. While it is unclear, this may be explained by the lack of testing specificity, training modality utilized, or measurement variability. A somewhat surprising finding was the training-induced increase in strength at the much higher velocity, compared to the RT velocity, of $300°$ s^{-1}. Typically concentric RT at slower isokinetic velocities ($\leq 75°$ s^{-1}) demonstrates little carryover to higher velocities in the knee extensors, especially a velocity as high as $300°$ s^{-1}, even with longer durations of training (Aagaard et al. 1996; Coyle et al. 1981; Englund et al. 2017). In contrast, our findings are similar to those of Kanehisa and Miyashita who reported strength increases of the knee extensors at $300°$ s^{-1} after 8 weeks of isokinetic training at $60°$ s^{-1} (Kanehisa and Miyashita 1983). Thus, while velocity specificity for strength adaptations is well established (Aagaard et al. 1996; Coyle et al. 1981; Kanehisa and Miyashita 1983), the degree of carryover for strength to other velocities is dependent on several factors related to the training protocol. Nevertheless, these findings expand on previous research demonstrating that age does not attenuate rapid (Barry et al. 2005; Hester et al. 2019) or maximal (Bemben and Murphy 2001; Christie and Kamen 2010; Knight and Kamen 2001) contractile adaptations of the trained musculature during short-term (≤ 6 weeks) RT. This is likely due to neural adaptations, which are expected to predominantly mediate short-term, RT-induced contractile improvements, occurring similarly between young and older adults (Kamen and Knight 2004; Knight and Kamen 2001).

There were some limitations associated with the current study. First, the sample size was relatively small, thus increasing the likelihood of underpowered analyses. However, despite the relatively small sample size, moderate effect sizes were demonstrated for most findings. Nonetheless, it would be worthwhile for future cross-education research, to

examine more diverse groups (e.g., sex comparison) considering age-related changes in neuromuscular properties may differ between populations. Second, surface electromyography would be required to ensure the contralateral leg remained relaxed during training rather than verbal instruction alone. However, previous studies using electromyography have demonstrated minimal muscle activation of the contralateral leg using methods and instructions similar to the current study (Devine et al. 1981; Hortobágyi et al. 1997). Lastly, the addition of a control group would have allowed for a precise distinction between true cross-education and a familiarization effect to the contralateral leg testing. Future studies examining the capacity of older individuals to obtain contralateral adaptations should include a control group to provide this potentially important distinction.

The current study determined that age does not attenuate RT-induced rapid or maximal contractile adaptations in the untrained knee extensors after unilateral training. Unilateral RT involving a ballistic intent was effective for increasing rapid contractile parameters and high-velocity strength regardless of age. These findings illustrate the capacity for short-term, training-induced adaptations in neuromuscular functioning, regardless of age, and the potential for unilateral RT to elicit improvements in maximal and rapid contractile characteristics of the untrained leg. Finally, the results indicate the potential for particular unilateral RT protocols to be used for older adults in rehabilitative settings to offset disuse-related reductions in contractile function, which are most dramatic in this population.

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